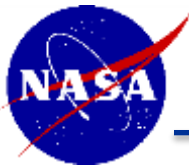


Preliminary Thrust Stand Measurements of an Ablative Gallium Electromagnetic (GEM) Thruster

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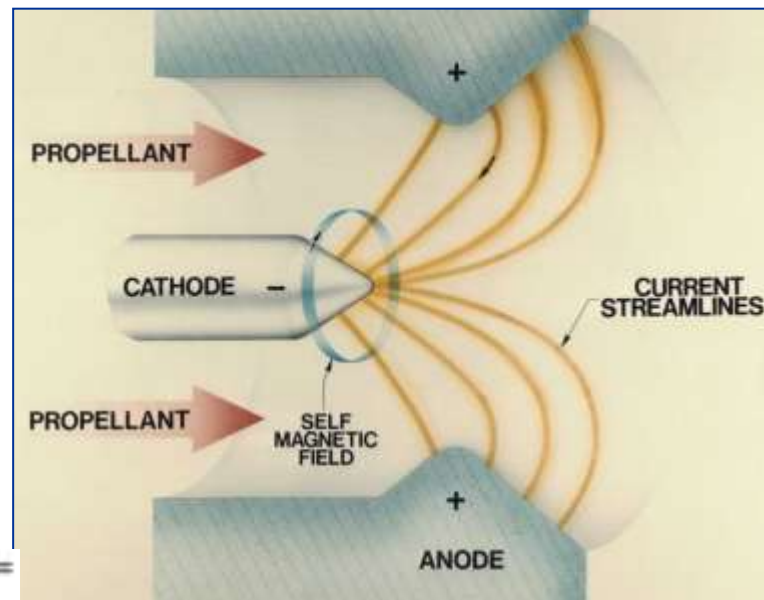
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Cleveland, OH 44135

Advanced Space Propulsion Workshop
28 Nov 2012
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Magnetoplasmadynamic Thrusters (MPDTs)

- Investigated since the 1960's, accelerates plasma via the Lorentz force
- Capable of high exhaust velocities (10-100 km/s), processing MW input power, high thrust densities
- Steady-state experiment demonstrated total impulse of 10^6 N-s (33 kW, 500 hours, $\eta = 16\%$)
- Plagued by cathode erosion, low efficiency (<40%)
- GEM thruster conceived to address these issues



	Self-field		Applied field	
	Quasisteady state	Steady state	Steady state	Steady state
Demonstrated total impulse, Na	2×10^4	3×10^4	1×10^6	5×10^4
Operating time, h	0.2	1	500	50
Cathode erosion rate, g/kA/kh	3600	100	9	0.14
$\mu\text{g/C}$	1	3×10^{-2}	3×10^{-3}	4×10^{-5}
Gas	NH_3	Ar	NH_3	H_2
Power, kW	1200	273	33	122
Specific impulse, s	2000	1100	1900	5900
Thrust efficiency	0.2	0.17	0.16	0.34

Sovey, J. Prop. Power, V. 7, No 1, p. 71



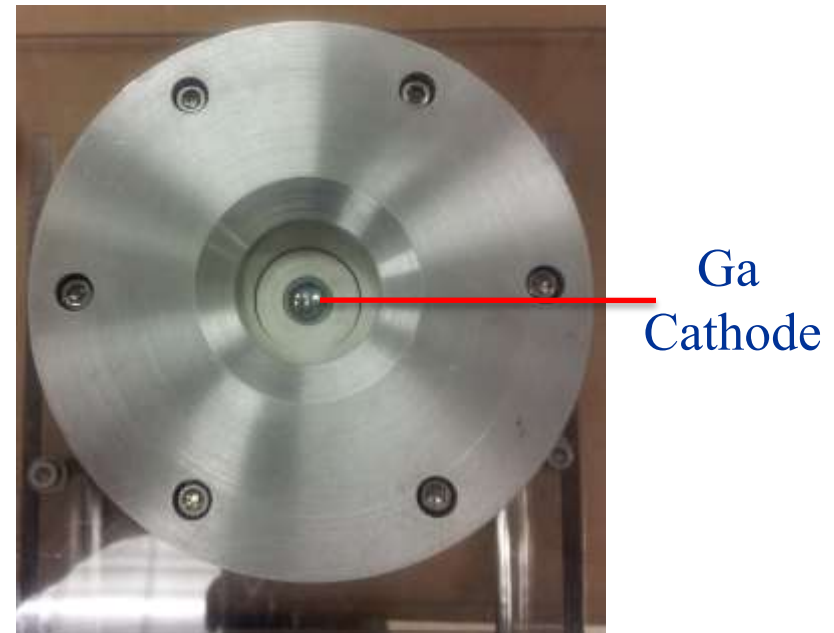
GEM (Gallium Electromagnetic) Thruster Concept

- First EP device to utilize gallium as a propellant
 - sparse research on gallium plasmas
- Approach: Feed liquid Ga through porous electrode to mitigate life-limiting cathode erosion
 - High power (MW), single shot experiments currently using solid Ga cathode to characterize mass ablated per pulse over various operating conditions
- Proof-of-concept experiments performed under NASA Fellowship (U. Illinois, MSFC 2006-10)
 - Langmuir probes, B-dot probes, emission spectroscopy used to characterize plasma plume

AIAA-2007-5855



Present Configuration





Why Gallium?

Gallium Physical Properties

Atomic Mass	70
Melting Point	30 °C
Boiling Point	2204 °C
Density	5.9 g/cm ³
1 st Ion. Pot.	6.0 eV
2 nd Ion. Pot.	20.5 eV



Proposed Advantages

Non-toxic and non-reactive

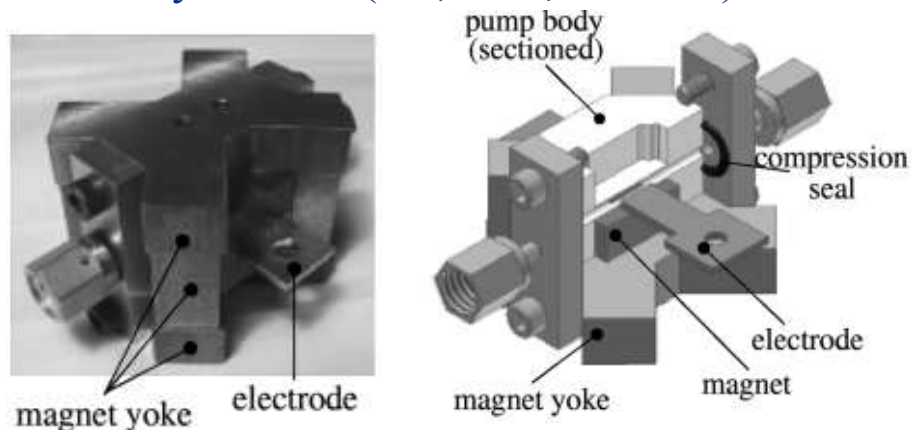
- readily handled in laboratory
- pumped (condensed) on baffle

Storability

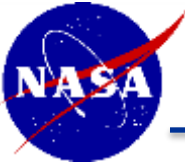
- can be stored as a solid or dense liquid
- large liquid temperature range (30-2204 °C)
- can be pumped electromagnetically*
- low vapor pressure (minimal boil off losses)

Low Ionization Potential

- easily ionized (6.0, 20.5, 30.7 eV)

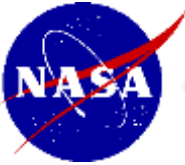


*Polzin, JPP, Vol. 24, p. 1141, 2008



Objectives & Diagnostics

- 1) Investigate the influence of geometry on ablative thruster performance (two geometries have been tested)
 - 2) Investigate energy loss mechanisms
 - 3) Develop model to accurately predict ablative thruster performance
- Discharge current
 - Arc voltage
 - Emission spectroscopy
 - Impulse bit
 - Mass bit



Electromagnetic (EM) Scaling Relations

Thrust:

$$T = bJ^2$$

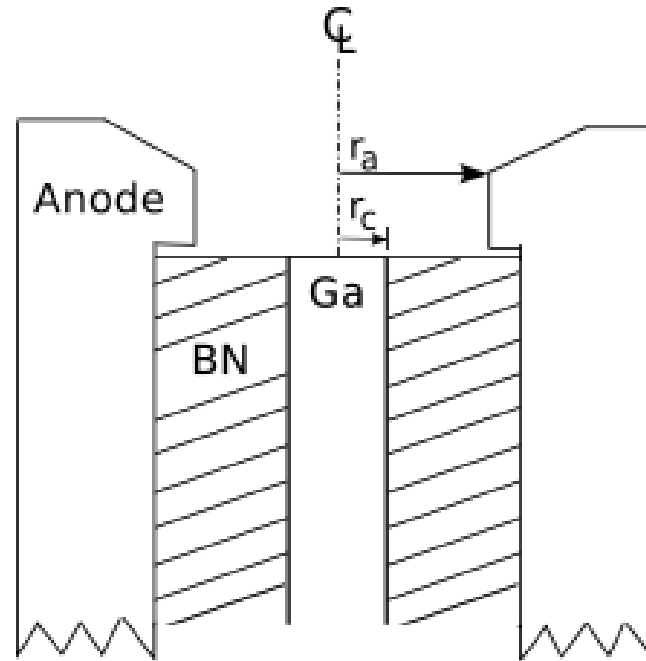
J = Discharge Current

$$b = \frac{\mu_o}{4\pi} \left(\ln \frac{r_a}{r_c} + \frac{1}{2} \right)$$

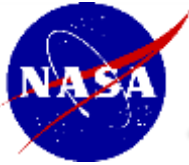
Exhaust velocity:

$$u_e = b \frac{J^2}{\dot{m}}$$

- charge carrier starvation limits maximum J^2/\dot{m} dot



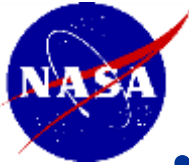
- Ablative thrusters -> mass flow is controlled by arc
- Prior experiments* found that: $\dot{m} \propto J^2 \Rightarrow u_e = \text{const}$
- **Electrode radius ratio r_a/r_c needs to be increased for better performance**
- approach used to increase the efficiency in ablative graphite MPDT**



Experimental Setup and Results

Electrode radius ratios of 2.8 & 3.5 have been tested

- Apparatus
- V-J characteristics
- Emission spectroscopy
- Impulse measurements
- Mass bit measurements
- Comparison with theory



GEM Thruster & Facility

- Thruster OD: 8.9 cm
- Thruster Mass: 8 kg
- Multiple annular electrodes fabricated to test various electrode ratios r_a/r_c
- Minimum cathode diameter limited by macroparticle ejection



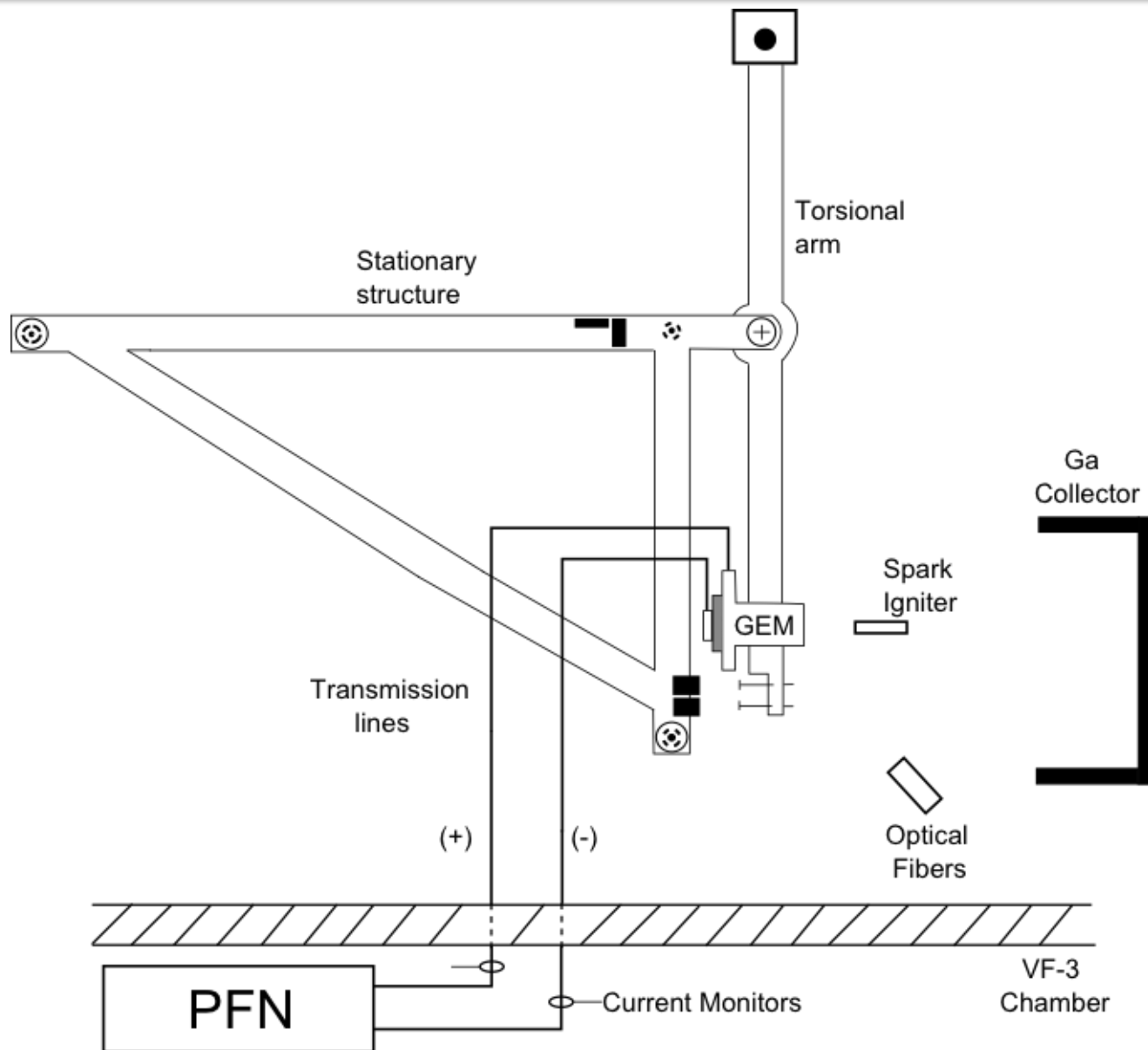
- 1.5 x 4.5 m vacuum facility
- Base Pressure: 3×10^{-6} torr

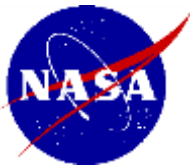


Thruster



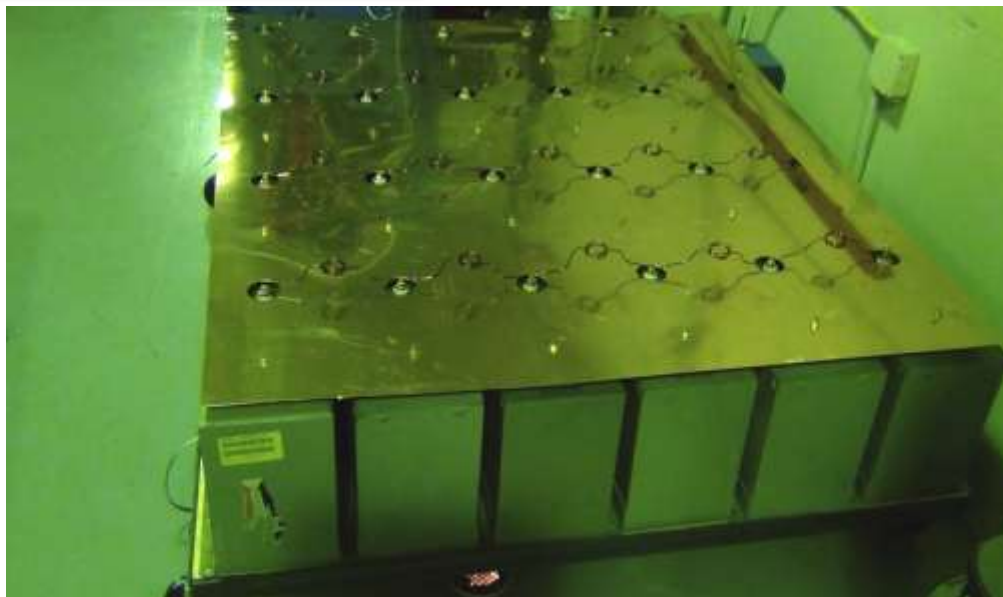
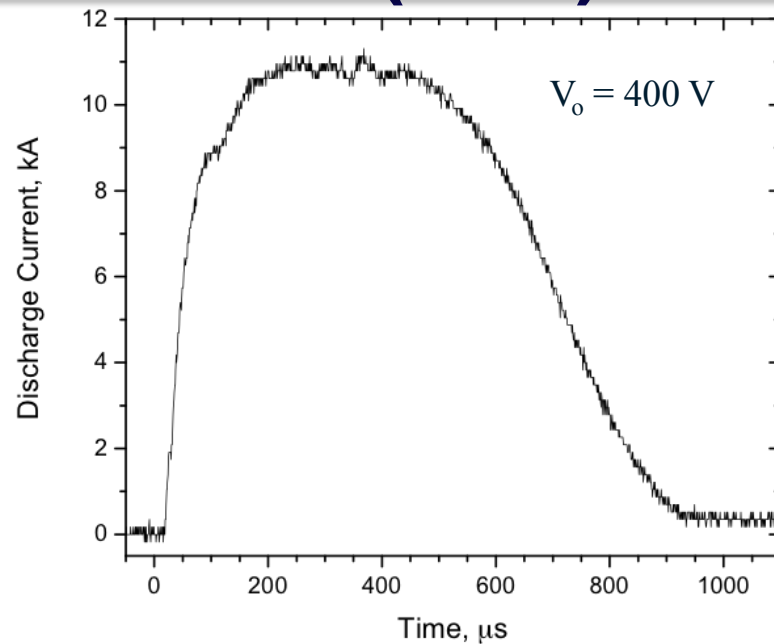
Experimental Apparatus





Pulse Forming Network (PFN)

# of Capacitors:	22
Dimensions (m):	1.3 x 1.4 x 0.4
Capacitance:	600 μF
PFN Impedance:	$\sim 12 \text{ m}\Omega$
Max Charging Voltage:	800 V
Peak Current:	35 kA
Max Energy:	4.2 kJ





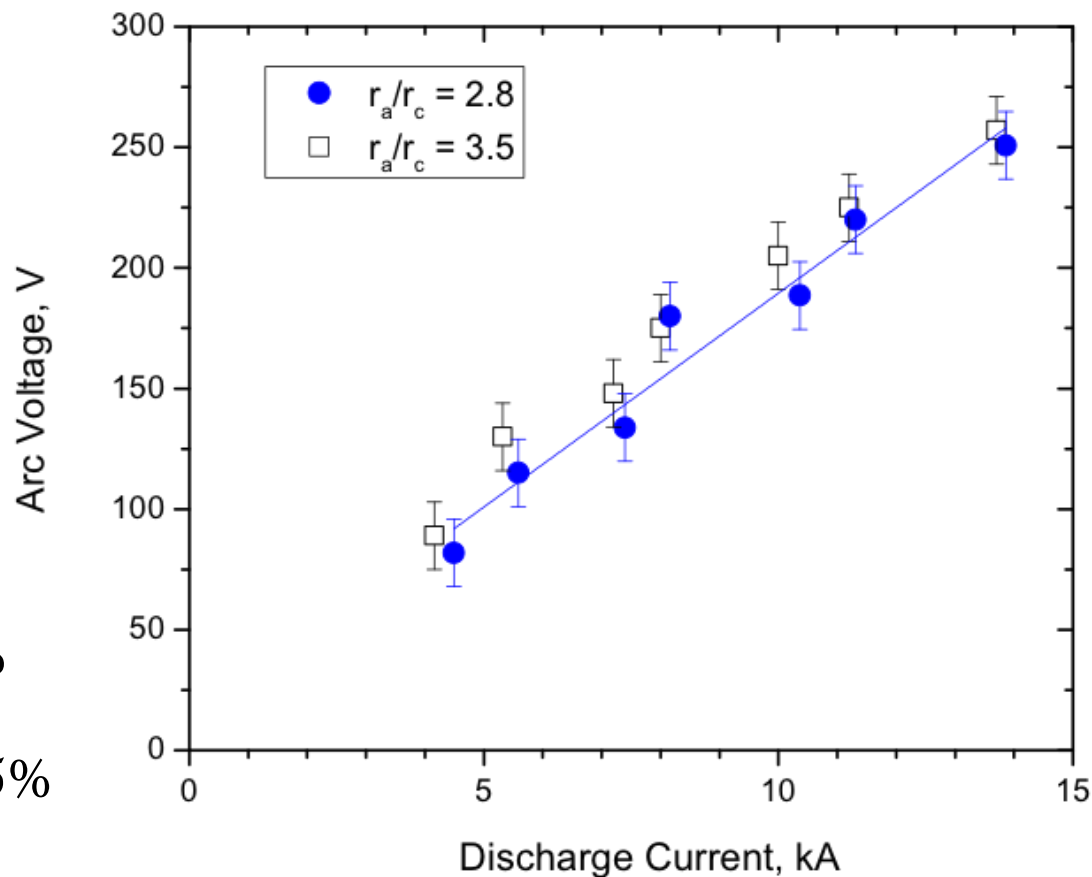
Voltage-Current Characteristics

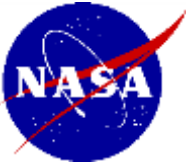
- Voltage linear with discharge current (consistent with $J^2/\dot{m} = \text{const}$)
- Voltage 2-3x higher than anticipated
 - Prior $Z_{\text{arc}} \sim 6\text{-}7 \text{ m}\Omega$

Energy Transfer Efficiency

Est. $\eta_t = (J^2 Z_{\text{line}} * \tau_p) / E_o = 95\%$

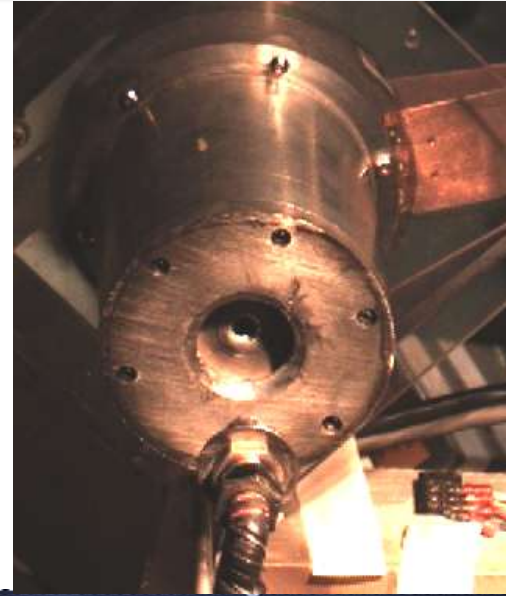
Exp. $\eta_t = \left(\int J(t)V(t) dt \right) / E_o = 85\%$





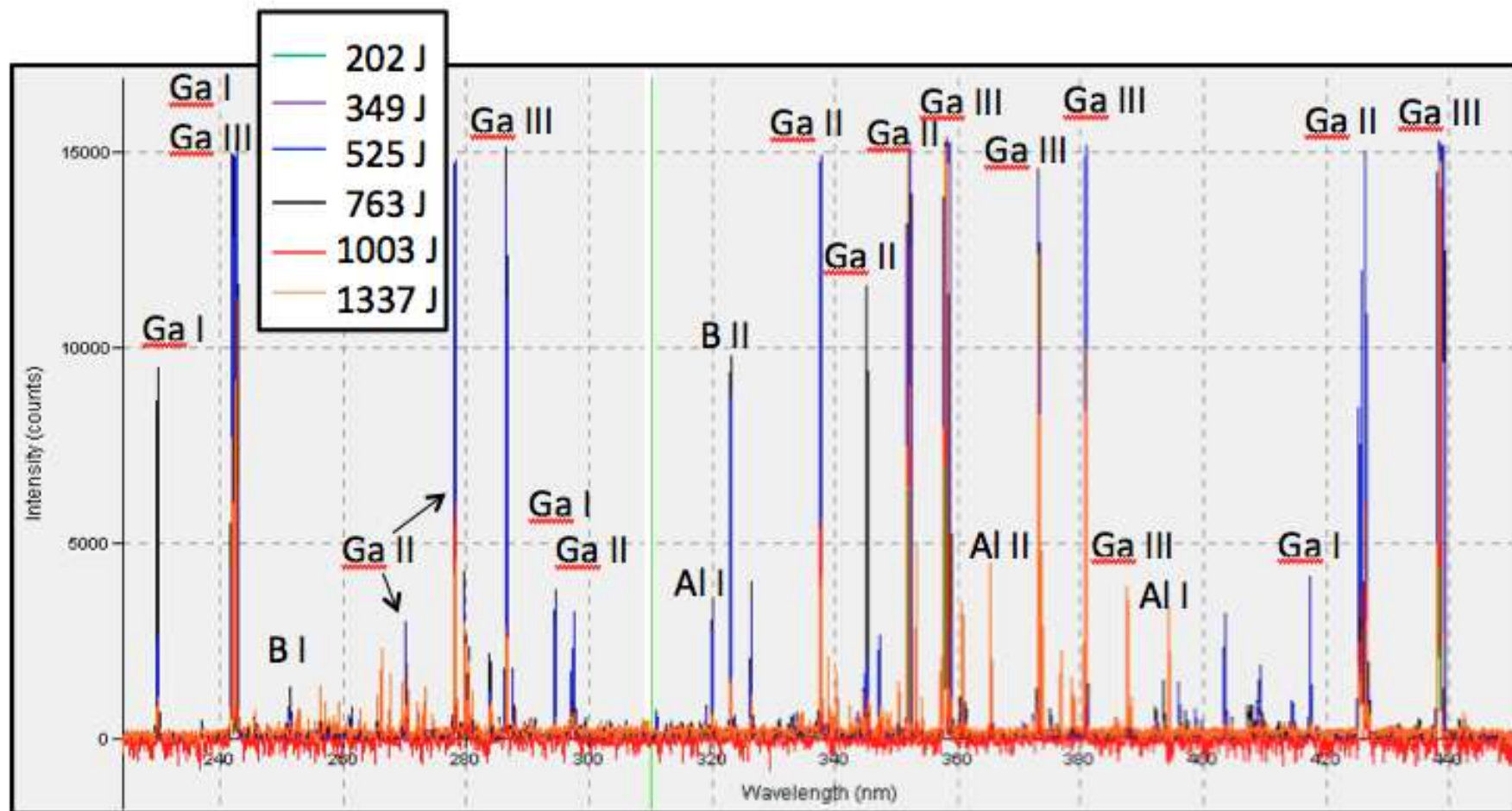
Emission Spectroscopy

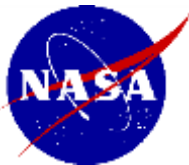
- UV/VIS, IR spectrometers used to characterize plasma plume from $E_0 = 0.2 - 1.8$ kJ
- Wavelength range: 220-850 nm
- Resolution: 0.07 nm
- Optical fibers located 30 cm from face of thruster
 - integrating over hot, warm, cold regions of the discharge



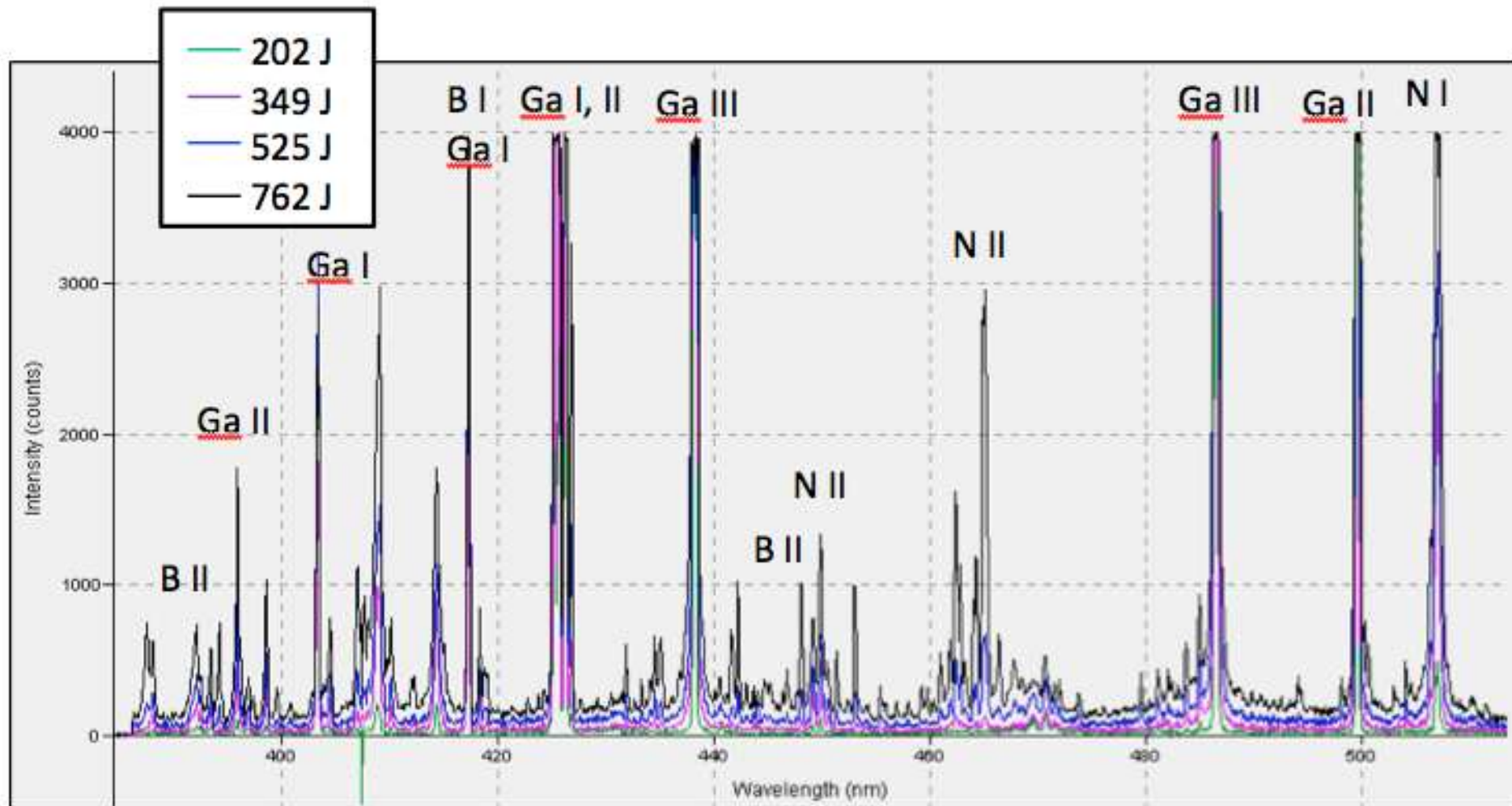


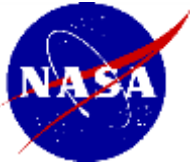
UV/VIS Spectrum (220-440 nm)





VIS Spectrum (400-520 nm)

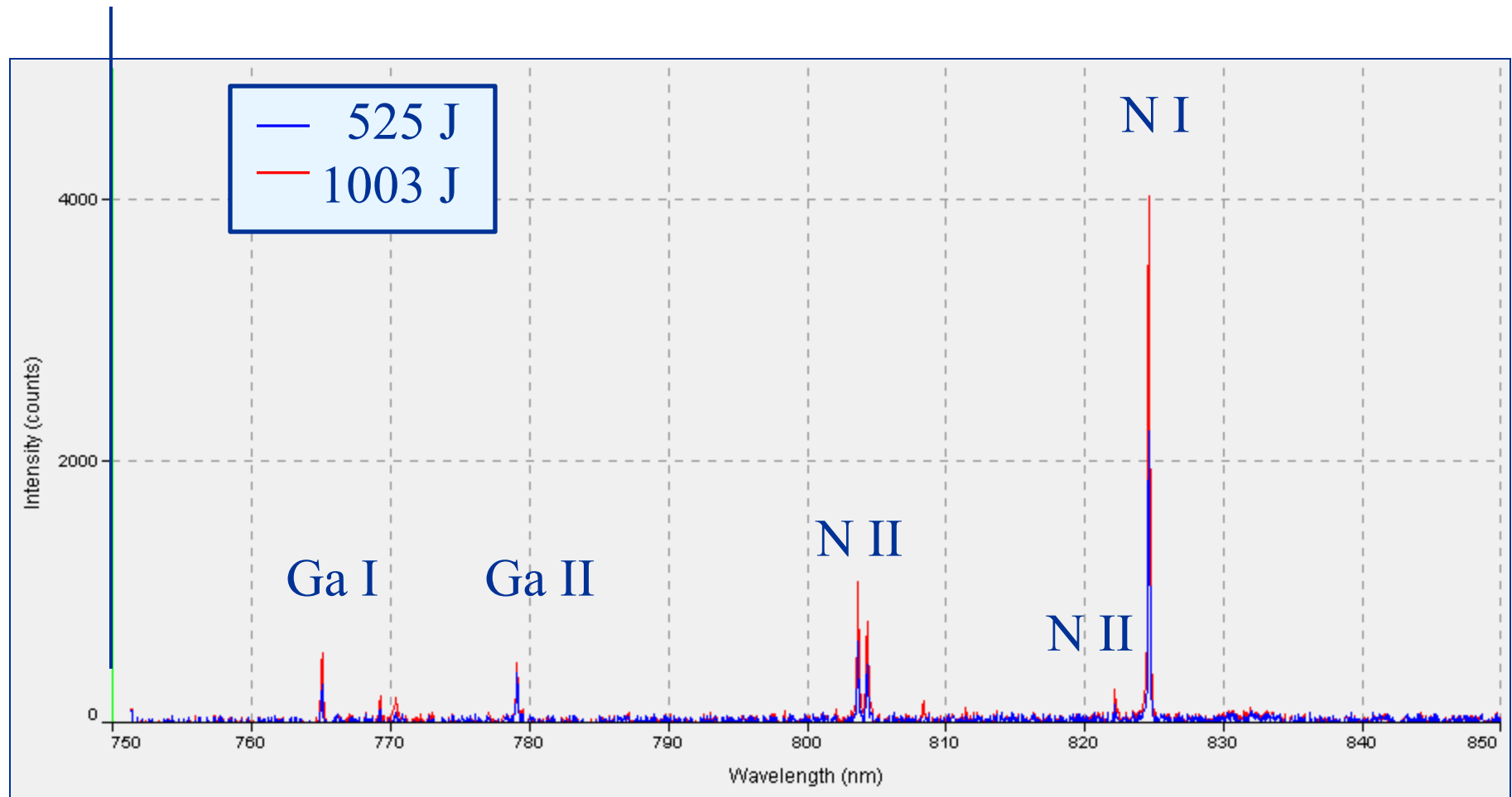


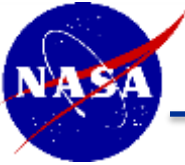


IR Spectrum (750-850 nm)

Future Work: 1) Ionization calculations

2) UV spectroscopy (< 200 nm) for Ga IV





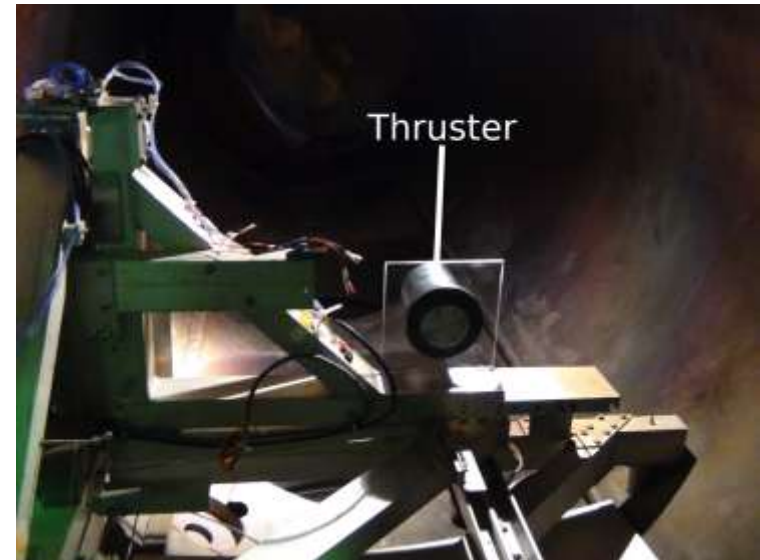
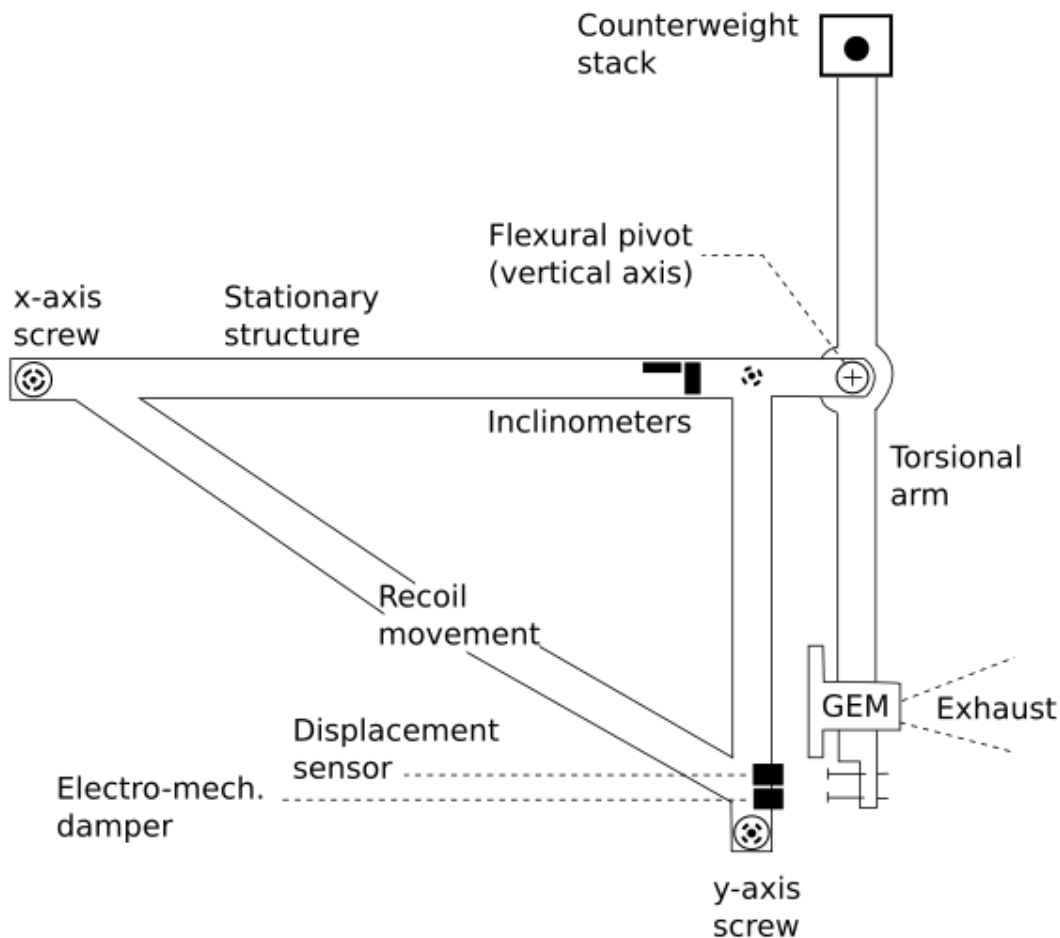
Impulse Measurements

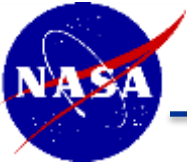
Has Successfully Tested:

1. LES-8/9 PPT
2. High Power PPTs

$$\text{Impulse bit: } I_b = \frac{kx}{\omega}$$

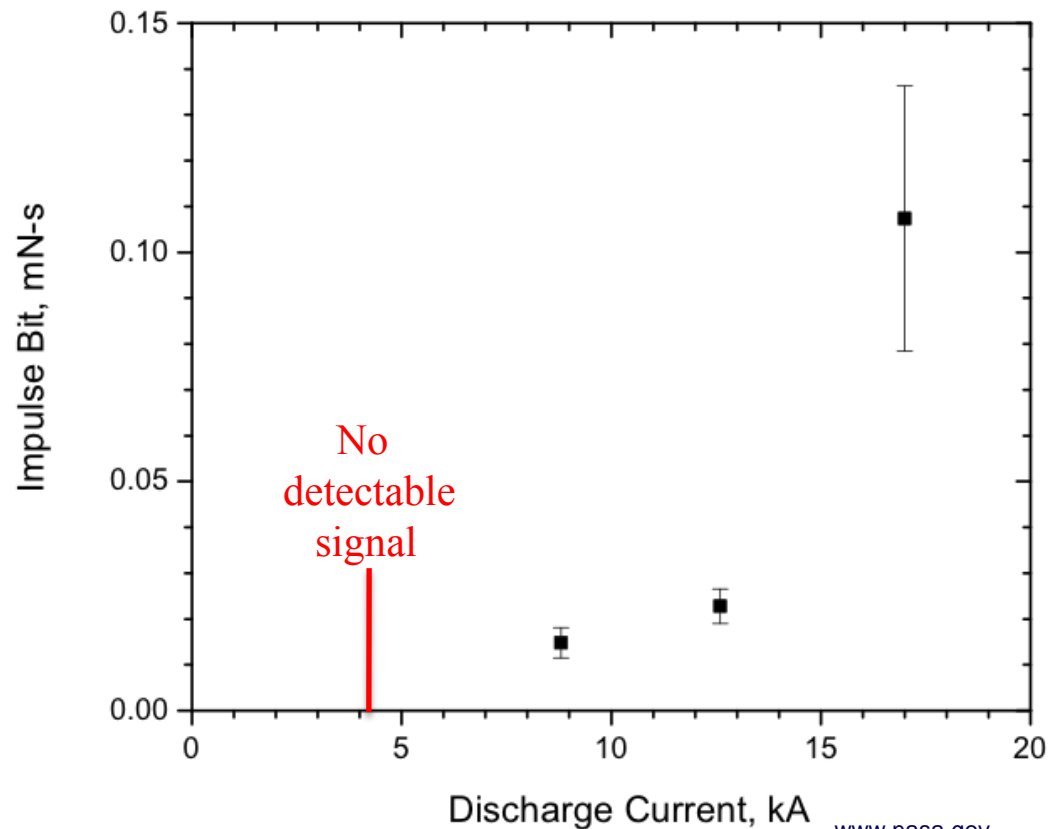
x = max deflection
 k = spring constant
 ω = natural freq.

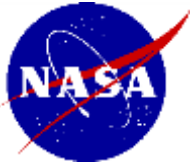




Magnetic Tare Measurements

- Mechanical flexure designed to eliminate magnetic perturbations
- Shorting bar placed across anode and cathode
- Impulse (I_{noise}) measured from 5 – 17 kA
- $I_{\text{EM}} \gg I_{\text{noise}}$

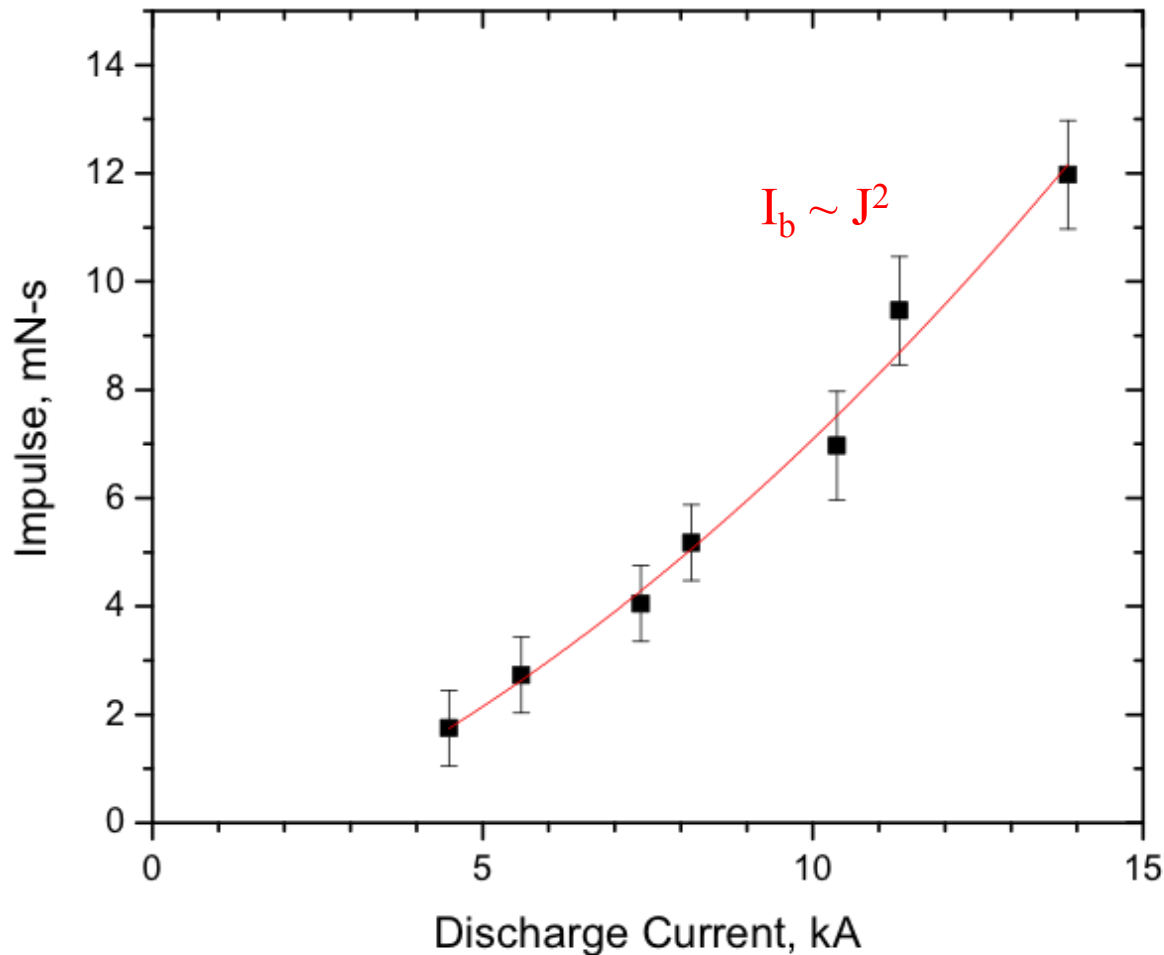


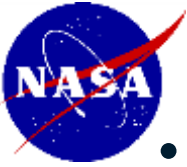


Impulse Measurements

$$\text{EM Theory: } I_b = \int T \, dt = b \int J^2 \, dt$$

- Data ($r_a/r_c = 3.5$) averaged over ten shots

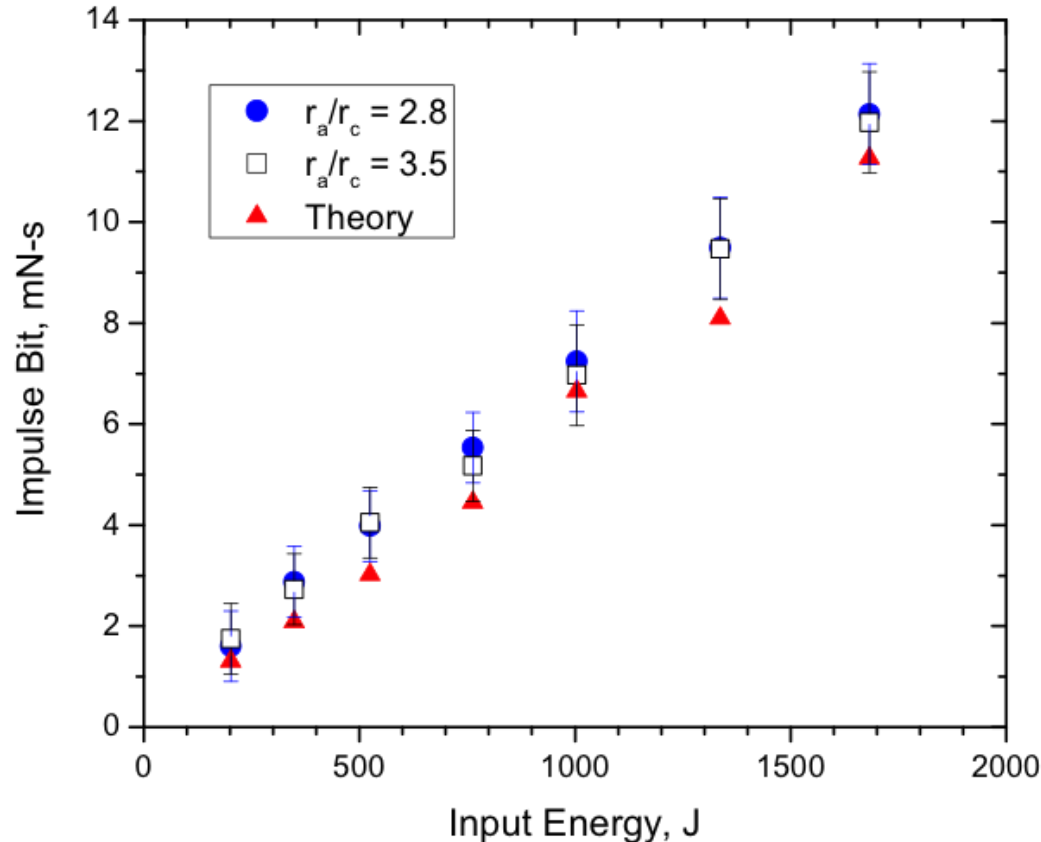




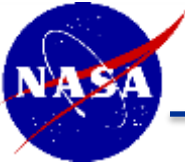
Impulse Measurements

- Impulse 10-20% higher than calculated value ($r_a/r_c = 3.5$ below)
- $r_a/r_c = 2.8 \rightarrow 3.5 =$ increases b by 16%
- no change in experimental impulse

*Thrust can depend on: current distribution, gasdynamic forces, \dot{m} dot



*Choueiri, JPP, Vol. 14, p 744, 1998

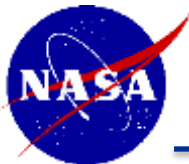


Mass Bit Measurements

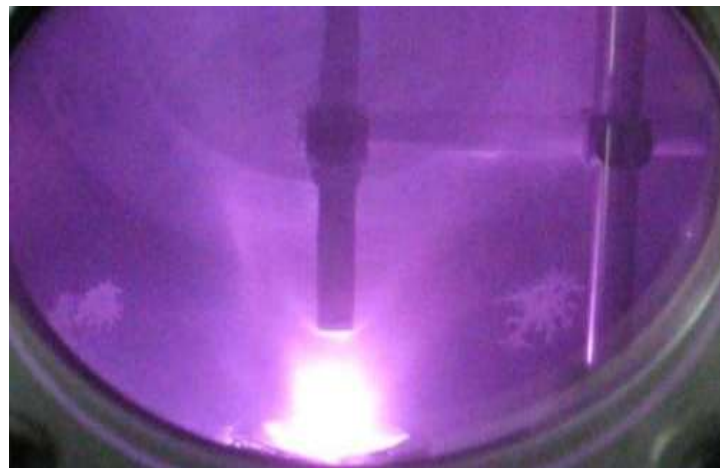
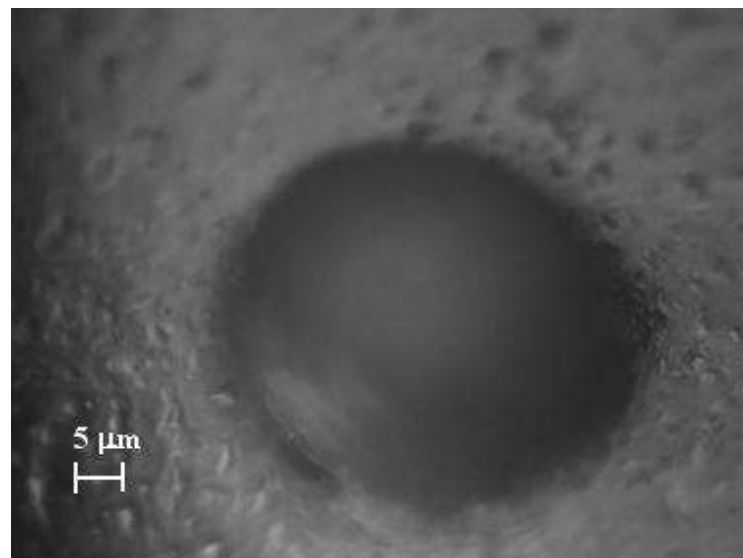
- Electronic balance used to weigh anode & cathode after (50-100) firings
- Gallium accounts for >95% of ablated mass
- At discharge current levels above ~ 10 kA
 - noticeable erosion patterns on outer anode
 - insulating sleeve placed around anode to prevent arcing to chamber
 - gallium macroparticle ejection
 - poor propellant utilization

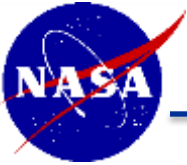
Anode Erosion





Macroparticle Ejection





First Order EM Performance Model

- Input Parameters:
1. Discharge Current: J
 2. $\dot{m} = f(J^2)$
 3. $b = f(\ln(r_a/r_c))$
 4. T_e (3.5 eV, prior experiments)
 5. $Z = 2$

Thruster Efficiency:

$$\eta = \frac{T^2}{2\dot{m}P} = \frac{b^2 J^4}{2\dot{m}(JV_{arc})}$$

Specific Impulse:

$$I_{sp} = b \frac{J^2}{\dot{m}g}$$

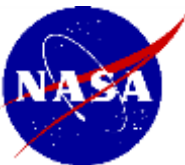
Arc Voltage:

$$V_{arc} = \frac{(b^2 J^4)}{2\dot{m}J} + \frac{\dot{m}(Ze\Sigma\phi_i + 3/2kT_e)}{Jm_{ion}} + V_{sheath}$$

Electro-
magnetic

Frozen
Flow

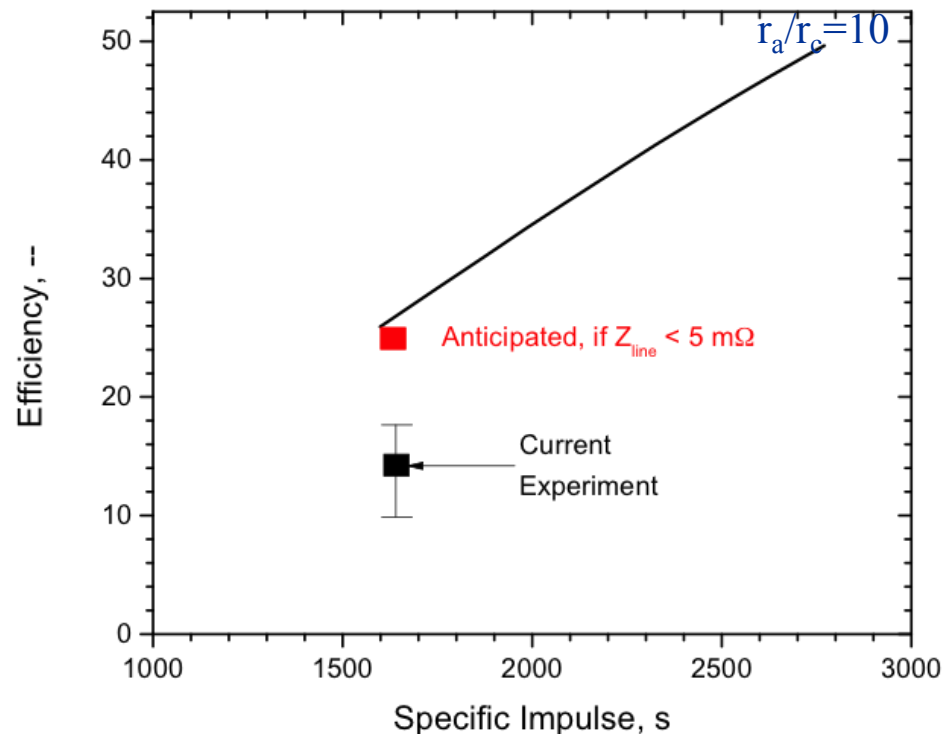
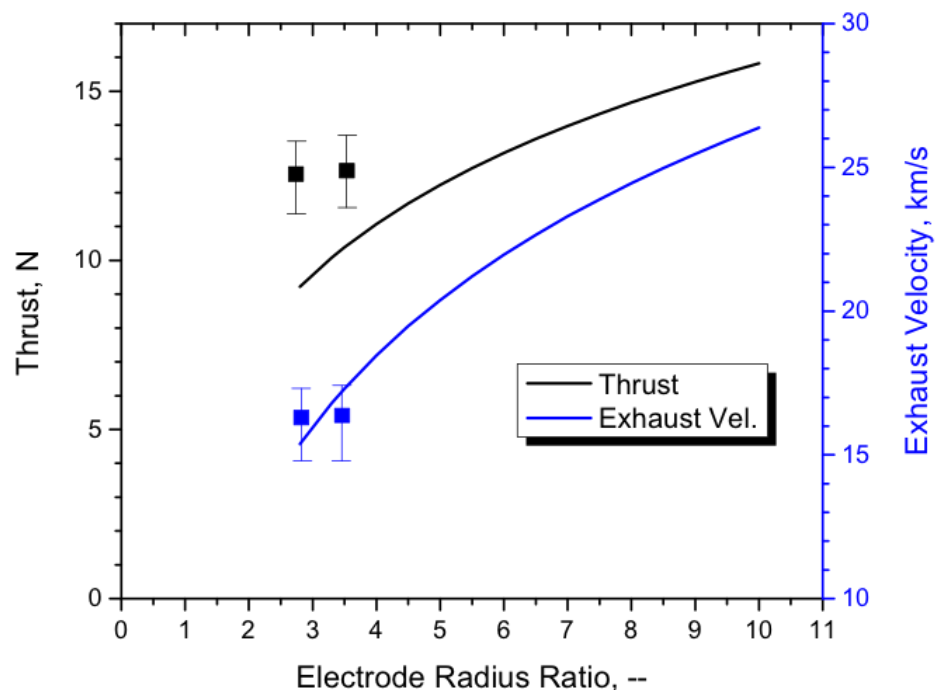
Sheath

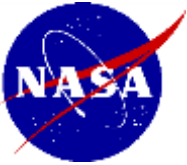


Performance Predictions

Operating Condition: $J = 8 \text{ kA}$, $P_{\text{in}} = 1.1 \text{ MW}$

- Thrust $\sim 10\text{-}25\%$ higher than predicted
- Specific impulse in good agreement with model
- Higher than anticipated measured voltage leads to 10% drop in η





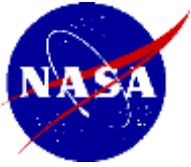
Future Work

- Investigate/ decrease transmission line losses
 - different HV feedthrough
 - shorten line length, increase area
 - SPICE modeling
- Improve propellant utilization
 - shorter pulse lengths may be needed to eliminate macroparticles
 - utilize different anode materials to minimize mass loss
- Use spectroscopy to investigate frozen flow losses
 - Compare excited states of Ga species
 - Detection of Ga IV requires < 200 nm spectroscopy
- Continue testing of larger electrode radius ratios
 - utilize b-dot probe to investigate current distribution

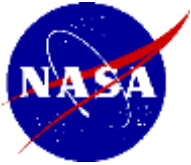


Summary

- GEM thruster conceived to address life-limiting cathode erosion present in MPDTs
- Successfully measured thruster impulse from $J = 4\text{-}14$ kA
 - impulse magnitude, J^2 trend consistent with EM theory
- Ga I-III present in discharge
 - BN and Al lines present at higher energy levels
 - further spectroscopic analysis will investigate frozen flow losses
- Model calculations predict an efficiency of 50% at an I_{sp} of 2800 s
 - Thrust and exhaust velocity within 20% of first order EM model
 - further work (b dot probes, arc voltage) needed to investigate thruster operation as anode geometry is varied



Questions?



Effective Quasi-Steady Pulse Length

Effective Time: $\tau_{eff} \equiv \frac{\int J^2(t) dt}{\langle J^2 \rangle}$

Thrust: $T = I_b / \tau_{eff}$

Mass flow rate: $\dot{m} = m_b / \tau_{eff}$